Time Domain Quadrature Interferometry Diagnostics on X-ray Diodes Driven by the RITS-3 Generator*

D. M. Ponce†, D.D. Hinshelwood, B. V. Weber
Naval Research Laboratory, 4555Overlook Ave. S.W.
Washington, DC 20375, USA

K. Hahn, M. Johnston, Z. Fettig
Sandia National Laboratories
Albuquerque, NM

A. Critchley and J. Threadgold
Atomic Weapons Establishment
Aldermaston, UK.

Abstract

This paper describes the setup, operation, data analysis procedures, and data results of a two-color (λ• = 532 nm and λ• = 1064 nm) quadrature laser interferometer used for the measurement of plasma densities produced by diverse x-ray diodes driven by the RITS-3 generator at Sandia National Laboratories. The nominal non-amplified signal resolution of the interferometer is of the order of 10^{-3} wavenumbers with the possibility to increase the sensitivity to the limit of detector shot noise of possibly 10^{-5} wavenumbers. The design is based on a Mach-Zehnder configuration and the NRL high sensitivity two-color interferometer. The quadrature interferometer is a space resolved instrument (< 1 mm spotsize) that provides the probed plasma line integrated index of refraction time history. The advantages of the quadrature interferometer are the ability to make a measurement regardless where the relative phase value of the interference pattern is when the measurement occurs and the ability to resolve fast phase changes over the slower phase envelope produced by external thermal and mechanical perturbations.

I. INTRODUCTION

Interferometry is a technique that has been used extensively to diagnose plasma phenomena. While setting up an interferometer is a straightforward task, one needs to decide on the type of interferometry to be performed, e.g. time resolved or space resolved, and adapt the instrument to the device or experiment where the plasma measurement is to take place. In interferometry it is of particular importance to be able to mitigate the sources of noise that naturally occur in a plasma experiment, such as mechanical noise and electromagnetic noise. Sometimes this adaptation requires for the researcher to devise alternative and clever ways to be able to use interferometry as a tool. This paper describes the setup, operation, data analysis procedures, and data results of a two-color (λ• = 532 nm and λ• = 1064 nm) quadrature laser interferometer used for the measurement of plasma densities produced by diverse x-ray diodes driven by the RITS-3 generator at Sandia National Laboratories (SNL). The quadrature technique was chosen for its ability to make a measurement at any point in the interferometer's phase cycle and also to be able to resolve fast phase changes that pertain to the plasma under study with respect to the slower phase envelope that is produced by external noise sources, all while maintaining excellent resolution (~ 10^{13} cm^{-2}). These features would facilitate measurements on the immersed B_z diode [1] that is under development at SNL. The firing of the B_z diode requires that a pulsed magnet producing several tens of Tesla be pulsed about 20 ms before RITS-3 fires. This experimental setup introduces two problems from the interferometric measurement point of view: the magnetic field would introduce a major mechanical perturbation making impossible a measurement if the interferometer requires a pre-set phase point to make a measurement; the firing sequence of the B_z diode would make it difficult to use the interferometer as the trigger of the experiment, making it difficult to maintain a pre-set phase point for such a long time between magnet pulse and diode current start time, even if all magnetic perturbations are mitigated. The quadrature technique

* Work supported by the Atomic Weapons Establishment and the U.S. Department of Energy through Sandia National Laboratories.

† National Research Council Associate at NRL

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **JUN 2005**	2. REPORT TYPE **N/A**		3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Time Domain Quadrature Interferometry Diagnostics on X-ray Diodes Driven by the RITS-3 Generator**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory, 4555Overlook Ave. S.W. Washington, DC 20375, USA**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.**			
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15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

circumvents these issues associated with the B_z diode. Although the quadrature interferometer was intended to be used in the immersed B_z diode, programmatic and scheduling factors delayed the interferometer's deployment on that diode. Instead, the quadrature interferometer was fielded on other diodes on RITS, like the self magnetic pinch diode (SMP) [2], the paraxial diode [3], and in the plasma filled paraxial diode [4]. Some of the experimental results on these diodes will be briefly discussed in the experimental results section. For details on the B_z , SMP, paraxial, and plasma filled paraxial, please refer to references [1],[2],[3], and [4] respectively and the references therein.

II. QUADRATURE INTERFEROMETER

A. Set up

The quadrature interferometer is set up in a Mach-Zehnder configuration with two Nd:YAG lasers (λ = 532 nm and λ = 1064 nm) each providing linearly polarized beams for two independent interferometers. Fig.1 shows a schematic of the interferometer setup. The interferometer is based on the design of the high-sensitivity interferometer described by Weber and Fulghum [5]. Each interferometer color produces a pair of interference patterns offset by $\pi/2$ radians, so for two-color there are four interference patterns or, equivalently, two pairs. We will refer to one pair of interference fringes for the operational description since both interferometers are identical in operation. The 45° polarized beam, after proper conditioning by a spatial filter, is focused to the experimental measurement point. This focused point defines the spatial resolution of the interferometer and is limited by diffraction. In practice, sub-millimeter spotsizes can be achieved. The line-integral is the accumulated phase change that scene beam picks up as the beam defines a chord across the probed medium's cross section.

The laser beam is passed through a first polarizing beam splitter where the vertical and horizontal polarization components of the laser beam are separated. One of these beams becomes the scene beam while the other is the reference beam. The only place where both of the colors can be made coincident is the scene beam. This only occurs when the scene or probe beam of each interferometer is combined just before entering the experimental chamber and separated just after they probe the plasma by a dichroic beam combiner.

The quadrature condition is achieved when the reference beam is passed through a quarter waveplate to produce a circularly polarized beam from the linearly polarized reference beam. Effectively what the quarter

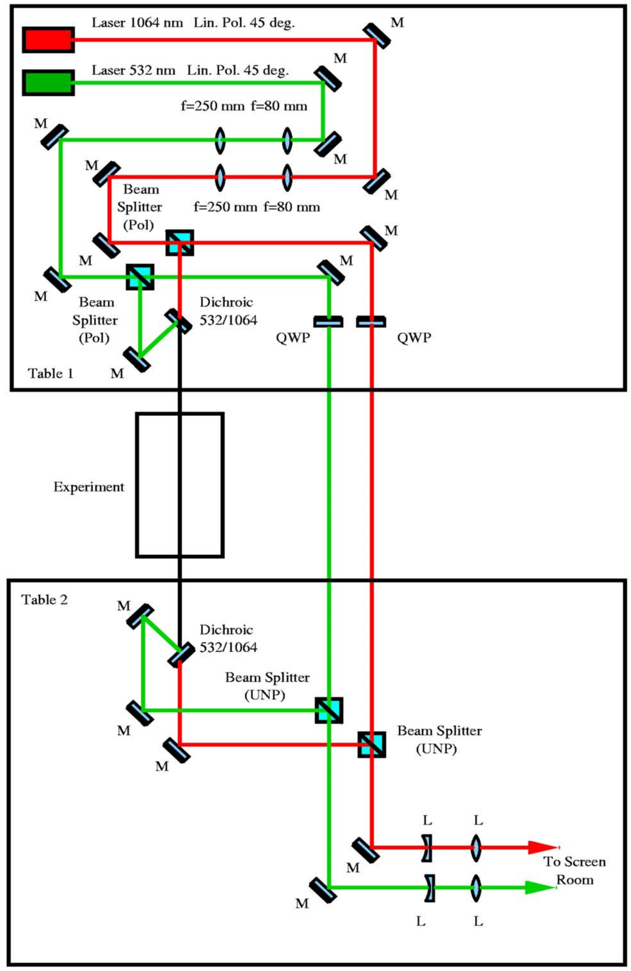

Figure 1.-Schematic of the Mach-Zehnder interferometer configuration showing details of the optics that make it operate in quadrature mode. M=mirrors, L=lenses, QWP=quarter wave plate, UNP=non-polarizing.

waveplate does is produce two orthogonal polarized components that are $\pi/2$ radians out of phase with each other. Both beams are then recombined at a non-polarizing beam splitter and are then directed to the detector set in a screen room. The detector setup consists of a polarizer cube pair, a mirror pair, and silicon photodiode pair [5].

B. Theory

The interferometer produces two fringe patterns in quadrature:

$$V1 = V_0\left(1 + \sin\phi\right) \tag{1}$$

$$V2 = V_0\left(1 + \cos\phi\right) \tag{2}$$

Equations (1) and (2) are the signals that the interferometer produces at the detectors. After proper normalization and the baseline, the signals should be bound between +1 and -1. Obtaining the phase is relatively simple, one just applies equation (3):

$$\phi = \arctan\left(\frac{V1 - V_0}{V2 - V_0}\right) \tag{3}$$

Phase jumps at when ϕ crosses the negative y axis ($\pm\pi$) are numerically counted and compensated for large phase shifts.

$$A = \frac{\sqrt{(V1 - V_0)^2 + (V2 - V_0)^2}}{V_0} = 1 \tag{4}$$

Equation (4) shows the amplitude function, ideally equal to unity, which is useful for determining any conditions that might hinder reliable measurements, such as beam fluctuations, noise from plasma light, or steering and refractive effects that the plasma might introduce on the scene beam.

III. EXPERIMENTAL

The interferometer was initially tested using the plasma from a cable gun set up on GAMBLE II. Fig. 2 shows the line density and the gun current trace. The measurement was made 2 cm from the gun tip and the gun was enclosed in a 1 cm diameter tube. The probe beam was 1 cm from the edge of the tube. The discharge voltage is 25 kV. Fig.2 also show bars bracketing the noise level in the measurement, with the noise being of electrical nature having its source at the gun pulser. Under the given conditions, it is possible to measure line densities of ~7x10^{13} cm^{-2}, but with careful noise mitigation, it would be possible to achieve sensitivities in the range of ~5x10^{12} cm^{-2}.

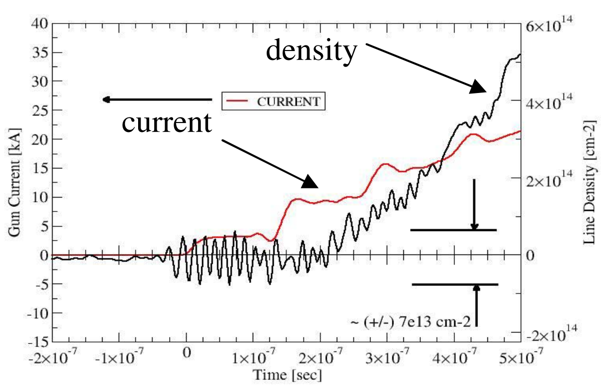

Figure 2. Line density from the plasma of a cable gun showing the instrument sensitivity. The high frequency noise is electrical. If this noise is suppressed, it is conceivable to achieve line density resolution within 10^{12} cm^{-2}.

The interferometer was fielded on RITS-3 and made measurements on the SMP, paraxial, and plasma filled paraxial diodes. Fig. 3 shows how the plasma produced by the electrodes in the SMP diode evolves to fill in the A-K gap and produce impedance collapse. Since the plasmas produced are of very high density, the line density measurement becomes secondary, but one can measure the plasma speed of propagation and estimate the time when the plasma shorts out the A-K gap. Notice that the x-ray signal on Fig. 3 is almost zero when the A-K plasmas meet in mid-gap. The generator current was the same for the three shots shown.

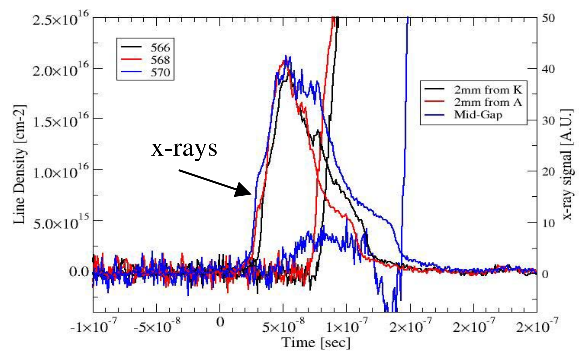

Figure 3. Plasma density measurements on the SMP diode at three different locations in the A-K gap. The A-K gap is 8.5 mm. X-ray signals are shown to determine relative timing of plasma arrival. The figure suggests plasma moving toward the center from both electrodes. It also suggests that the x-ray decrease is associated with plasma shorting out the diode.

For the paraxial diode, it is of interest to measure the plasma density induced in the gas cell by the electron beam. Certainly, the degree of gas ionization will determine the beam focus and subsequent spotsize. Fig. 4 shows an attempt to measure this plasma density. What renders this measurement suspect is the negative dip on the measured line density at the beginning of the x-ray pulse. While the problem was not solved completely during the experimental run, the effect was attributed to x-ray induced phase shift of the interferometer's scene beam. The x-rays, if not shielded properly, will affect the glass on the window ports where the scene beam goes through. The paraxial diode hardware was such that x-rays might have been at fault. Nevertheless, with this measurement one gains insight into the possible plasma evolution within the gas cell.

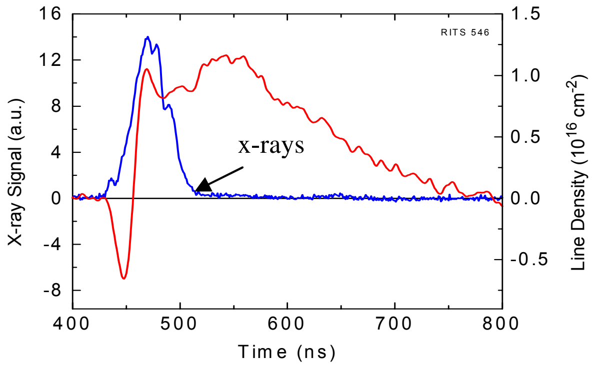

Figure 4. Plasma line density measured inside the gas cell in the paraxial diode. X-ray induced phase shift on interference signal may produce negative density values at the beginning of the x-ray pulse. While data is suspect, interferometer shows qualitatively the evolution of the plasma produced by the electron beam ionization.

Another mode of the paraxial diode under investigation is to have plasma instead of neutral gas in the transport cell during the passage of the electron beam. The plasma will provide for beam neutralization and enhance beam focusing. Fig. 5 shows a current trace of the 25 kV discharge that produces the plasma inside the 500 mtorr of hydrogen gas cell. Also shown are three values of the plasma density, as measured by the interferometer, at the three particular times shown along the current trace. The line density was abel inverted to produce the actual density values [4].

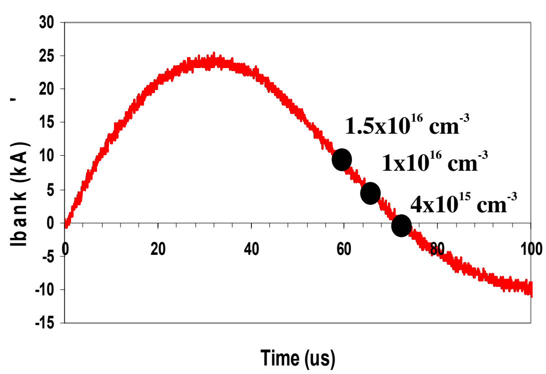

Figure 5.- Current waveform of plasma discharge in the plasma filled paraxial diode and plasma densities measured with the quadrature interferometer at three times.

IV. SUMMARY

A Mach-Zehnder interferometer utilizing a quadrature technique was developed and implemented to make plasma density measurements on diverse diodes fielded on the RITS-3 generator at Sandia National Laboratories. The most notable advantage of using the quadrature technique is the ability to make measurements of fast phenomena on top of slow (thermal and mechanical) perturbations. While the instrument proved to be useful in a variety of circumstances, it became clear that time and effort needs to be invested to adapt the instrument to each particular case.

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